The effects of hydration on cognitive performance during a simulated wildfire suppression shift in temperate and hot conditions

Michael A. Cvirn [1]

*Address correspondence to: Michael Cvirn

E-mail: annonymous1986MC@mail.com

Abstract

The effects on dehydration and cognitive performance from passive heat and/or physical activity are well established in the laboratory. However, previous research has not determined the effect on cognitive performance of hydration, thermoneutral and hot temperatures in the presence of physical activity. Personnel working in occupations such as wildland firefighting are often exposed to such conditions. This study aimed to investigate the effects of temperature and dehydration on cognitive performance during a simulated wildfire suppression shift. Seventy-three volunteer firefighters (35.7 ± 13.7 years, mean ± SD) participated in a simulation of a wildfire suppression tour in either *control* (i.e., temperate or thermoneutral) (n = 45) or *hot* conditions (n = 28). During the simulation, participants completed three physical work circuits involving repeated bouts of self-paced physical work activities based on real wildfire suppression duties. Each physical work circuit was followed with a cognitive test battery and hydration measurement using U_{sg} analyses. Temperatures were set between 23-25°C for the *control* condition and 33-35°C for the *hot* condition. Cognitive performance was measured using the psychomotor vigilance task and the Stroop task. Performance declined on measures of PVT when participants were *approaching dehydration* and in the heat, whilst for Stroop RT on non-matching word-pairs, performance was impaired when *approaching dehydration* late in the afternoon, irrespective of external temperature conditions. Firefighters may be most at risk of deterioration of simple mental functions in the heat whilst *approaching dehydration*, however may be at risk of complex mental impairment if *approaching dehydration* late in the day (i.e., 18:00 h), irrespective of the environmental temperature.

Keywords: hydration, heat, firefighter, cognitive performance, temperature, physical activity.

1. Introduction

Wildland fires are known for extreme heat, low humidity and high wind speeds (Aisbett, Wolkow, Sprajcer, & Ferguson, 2012). In order to suppress wildfires, firefighters often work shifts of up to 16 hours (Cuddy, Gaskill, Sharkey, Harger, & Ruby, 2007; Gaskill & Ruby, 2004). Performing physically demanding manual handing tasks (Phillips et al., 2012) in temperatures as high as 46.4°C (Teague, McLeod, & Pascoe, 2010), while wearing heat retaining personal protective clothing and equipment (Barr et al., 2010). However, not all firefighting operations are conducted in extreme temperatures. For example, during the February 2009 fires in Victoria, Australia, suppression and blacking out activities were ongoing in temperatures as low as 15.8°C (Raines et al., 2012). Given the variation in the ranges of ambient temperatures firefighters are exposed to during wildfire suppression (Raines et al., 2012) the effects of temperature on firefighters' health and safety is an important consideration for fire agencies. Examining firefighters' mental performance whilst performing physical work in different ambient environments could directly inform agencies' decisions in relation to the productivity and safety of their crews. Further, such information could lead to customised safety procedures (e.g., rest breaks and fluid provisions) for different ambient temperatures. Also, this knowledge could be used to strengthen existing protocols or policies.

However, performance may not only be affected directly by ambient temperature, but also dehydration, which in turn is affected by the ambient environment. Previous research (Hendrie et al., 1997; Raines, Snow, Nichols, & Aisbett, 2015; Raines et al., 2012, 2013) has identified that wildfire suppression can lead to dehydration in Australian wildland firefighters, although cognitive performance has not yet been examined. For fire agencies striving to implement safety controls it is important to determine the risks to firefighters' cognitive function and therefore safety when exposed to ambient temperature, physical activity, and dehydration, or a combination (Cuddy, Ham, Harger, Slivka, & Ruby, 2008; Hendrie et al., 1997; Raines et al., 2012, 2013; Ruby, Schoeller, Sharkey, Burks, & Tysk, 2003).

While the effects on cognitive performance of exercise in more cooler or temperate conditions with dehydration have been well documented in the laboratory in healthy young norms, studies show disparate results. In temperatures of 20-21°C, regardless of body mass (B_m) losses of 2.2% and 4.1%, in fluid and no fluid exercise conditions, cognitive performance did not vary as a function of hydration status (Grego et al., 2005). In contrast other research showed dehydration in the range of 1-2% B_m loss from exercise in temperate conditions degraded cognitive performance, compared to exercise whilst maintaining euhydration (Ganio et al., 2011). Similarly, the effects of dehydration induced via exercise or passive heat alone to 2.8% of B_m have shown comparable cognitive performance impairments compared to hydrated individuals (Cian, Barraud, Melin, & Raphel, 2001; Cian et al., 2000).

Further, results from studies on the effects of heat and exercise induced dehydration on cognitive performance also show inconsistencies. Studies have reported dehydration losses of 2-4% B_w in ambient heat with physical activity were associated with cognitive performance impairments (Gopinathan, Pichan, & Sharma, 1988; Sharma, Sridharan, Pichan, & Panwar, 1986). In contrast other research demonstrated B_m losses of < 2% from exercise in the heat were associated with no differences in cognitive performance compared to hydrated controls (Serwah & Marino, 2006). Similarly, no effects on cognitive performance have been reported from B_w losses of up to 3.7% from exercise in a heated chamber in conditions with and without fluid replacement (Tomporowski, Beasman, Ganio, & Cureton, 2007). Hence, collectively these studies on the effects of heat and exercise induced dehydration on cognitive performance show different results, reporting either impairments (Gopinathan et al., 1988; Sharma et al., 1986), or no change (Serwah & Marino, 2006; Tomporowski et al., 2007).

To the authors' knowledge, there is no existing laboratory (or field) research utilising a protocol comparing both cool and hot variations in external temperatures simultaneously with physical activity and dehydration to determine the effects on cognitive performance. Hence the effects of working physically demanding jobs in the heat, or in milder temperatures while being either hydrated or dehydrated on mental work capacity, for firefighters or other populations, is still unknown. For fire agencies aiming to put in place occupational health and safety controls it is important to understand if mental functioning declines with hydration status. To ensure ecological validity, these effects are usually studied in the field, however as temperature, wind, and the severity of the emergency situations are all highly variable it is not feasible to use field data to isolate the effect of specific temperatures during manual handling physical activities on cognitive performance. Therefore, the purpose of the present study was to conduct a wildfire suppression laboratory simulation in hot and thermoneutral ambient temperatures to determine the effect of resulting hydration levels on cognitive performance.

2. Methods

2.1. Participants

Participants (*n* = 73, 62 m, 11 f; age = 35.7 ± 13.7 y; BMI = 27.8 ± 4.5 kg/m^2) were recruited from the Country Fire Service, Country Fire Authority, Tasmania Fire Service, New South Wales National Parks and Wildlife Service, and Australian Capital Territory Fire and Rescue. Firefighters participated in a wildland fireground deployment simulation and were assigned to one of two conditions ─ either *control* or *hot* (characteristics reported in Table 1). Ethics approval was obtained from the CQUniversity (H12/01-016) and Deakin University Human Research Ethics Committees (2010-170).

Table 1

Demographics of firefighters in the *control* and *hot* conditions. Values are in mean ± SD.

	control	*hot*
n	45	28
Age (y)	36.4 ± 14.2	34.7 ± 13.2
BMI (kg·m^{-2})	28.3 ± 4.8	26.9 ± 4.0
Male:Female	38:7	24:4

2.2. Procedure

Participants arrived at 19:00-20:00 h on the baseline night and completed numerous familiarisation trials on the cognitive tasks to eliminate any potential practice effects. Participants were then provided with an 8 h sleep opportunity from 22:30-06:30 h. In the morning from 08:15-10:30 h participants completed further cognitive task familiarisation and the experimental protocol was initiated at 11:30 h, where the climate controlled laboratory temperature either remained constant between 23-25°C for the *control* condition or was increased to 33-35°C, for the *hot* condition. Temperature was monitored using a wireless temperature and humidity logger (HOBO ZW_003, One Temp Pty Ltd, Australia), data receiver (HOBO ZW_RCVR, One Temp Pty Ltd, Australia), and associated software (HOBO Pro Software, One Temp Pty Ltd, Australia).

The simulated fireground shift commenced at 12:30 h and consisted of three two hourly sessions comprised of physical work, and physiological and cognitive testing from 12:30-14:30 h, 14:30-16:30 h, and 16:30-18:30 h. Each session was comprised of a 55 minute physical work circuit involving wildland firefighter suppression tasks (for a detailed methodology and the effects of sleep restriction on physical work the reader is referred to Vincent et al., 2015), 20-25 minutes of physiological testing (for a detailed methodology and the effects of heat on physiological testing the reader is referred to Larsen, Snow, & Aisbett, 2015), and 20-25 minutes of cognitive testing followed by a 15-20 minute rest period. For the PVT and Stroop task the trials were conducted at the same overlapping times each day 13:50 h (early-afternoon trial), 15:50 h (mid-afternoon trial) and 17:50 h (late-afternoon trial).

2.3. Psychomotor Vigilance Task

Cognitive performance was measured using the psychomotor vigilance task (Dinges & Powell, 1985). The PVT specifically provides an automatic measure of sustained attention (Dorrian, Dinges, & Rogers, 2005). The PVT was tailored for use on a personal digital assistant by the Walter Reed Army Institute (Thorne et al., 2005). A validated five minute PDA substitute version of the PVT was presented on the Tungsten E PalmPilot (Palm Inc., Sunnyvale, California; Lamond, Dawson, & Roach, 2005; Lamond et al., 2008; Roach, Dawson, & Lamond, 2006). The task measures how fast subjects respond to a luminous-white-light presented on a black target stimulus. The display presents the visual stimulus, counting from zero to 60 seconds in 10 millisecond intervals. The PVT inter-stimulus interval varies randomly between 2,000 and 10,000 milliseconds, producing approximately 45 reaction times per five minute trial. The dependent variables (DVs) for the PVT were mean RT (ms) and the number of lapses (i.e., RTs > 500 ms).

2.4. Stroop task

The Stroop task, a measure of the executive function of response inhibition, has previously been used in research on dehydration (Szinnai, Schachinger, Arnaud, Linder, & Keller, 2005). The Stroop task consisted of two by two minute conditions, requiring participants to respond to the font colour via the corresponding colour on an alphanumeric keypad. For the matching word-pair condition the colour name was presented in the corresponding colour (e.g., 'GREEN' was presented in green font) for the non-matching word-pairs the colour name was presented in a non-corresponding colour (e.g., 'RED' was presented in blue font). Colour-word displays were made up of the words 'RED, BLUE, GREEN or YELLOW' presented on a standard 17" screen (resolution, 1280p x 800p). The DVs derived for the Stroop task were percentage correct and mean RT (ms) for both matching and non-matching word-pairs.

2.5. Activity data

Actiwatch-64 (Mini-Mitter Philips Respironics, Bend, OR) or Actical Z-series (Mini-Mitter Philips Respironics, Inc.) devices were worn on the non-dominant wrist, prior to and during the simulation, sampling movement at 32 Hz with an omnidirectional piezoelectric accelerometer. Accompanying software (Actical® version 3.0; Mini-Mitter Philips Respironics, Inc.) was used to analyse epoch-by-epoch time stamped physical activity counts for each participant. Physical activity was measured by summing the activity count for each 60 second epoch over the 55 minute physical work circuit before each cognitive test session, providing a total activity count measure for each circuit.

2.6. Hydration testing

Participants were provided *ad libitum* access to fluid, electrolytes and food, with portions developed in close consultation with Australasian Fire and Emergence Service Authorities Council representatives (Ferguson et al., 2011). Urine samples were collected in the break opportunities provided at the end of each test session (i.e., 14:30 h; 16:30 h; and 18:30 h). However since participants were not always able to void urine at the requested times not all potential U_{sg} samples (one for each three 2 h testing session per participant) could be obtained.

Hydration values were determined by performing a U_{sg} analysis using a portable refractometer (Atago, Japan). Prior to U_{sg} analysis researchers placed a drop of distilled water on the face of the prism, as standard, to adjust the instrument to 1.000 grams per milliliter ($g \cdot mL^{-1}$). Each of the U_{sg} samples and the corresponding cognitive performance values for the relevant test session were assigned a hydration status. U_{sg} values 1.000-1.019 $g \cdot mL^{-1}$ were classified as euhydrated, whilst values ≥ 1.020 $g \cdot mL^{-1}$ were classified as non-euhydrated (*approaching dehydration*). Samples were classified according to the published ranges with previous authors recommending a U_{sg} of < 1.020 $g \cdot mL^{-1}$ as a euhydrated state (Cheuvront, Kenefick, Sollanek, Ely, & Sawka, 2013) and a U_{sg} range of 1.022-1.034 $g \cdot mL^{-1}$ indicative of dehydration (Cheuvront, Ely, Kenefick, & Sawka, 2010). There has been some debate regarding dehydration assessment in recent studies, for their alternative views the reader is referred to Armstrong, Maughan, Senay, and Shirreffs (2013) and Cheuvront, Kenefick, and Charkoudian (2013).

2.7. Statistical analyses

The method of splitting the data and analyses were based on previous research methodologies (Dorrian, Hussey, & Dawson, 2007; Dorrian, Roach, Fletcher, & Dawson, 2006; Dorrian, Roach, Fletcher, & Dawson, 2007). However, this method resulted in groups of uneven size for both the *control* condition (euhydrated, *n* = 37; and non-euhydrated, *n* = 18) and for the *hot* condition (euhydrated, *n* = 25; non-euhydrated, *n* = 7). As there is potential to violate the assumption of homogeneity of variance, two checks were conducted to ensure robustness and therefore deflating the risk of a Type 1 error. First, the ratio of largest to smallest groups was less than 4:1, and secondly, the ratio of variances in each cell was less than 10:1 (Tabachnick & Fidell, 2007). Since these conditions were met, there was no need to randomly exclude cases in low and moderate groups to even out numbers, thus avoiding any unnecessary data loss. Importantly, however, this method of splitting the data also resulted in repeated measurements for individual firefighters within hydration statuses for both conditions. To account for this ‘participant ID’ was specified as a random effect in order to control for the inter-correlated observations within hydration statuses for firefighters in both conditions.

Since previous research has shown exercise can facilitate aspects of cognitive performance (Tomporowski, 2003) a preliminary mixed model analysis of variance was conducted to assess differences in physical activity with 3 fixed factors of condition (2 levels – *control, hot*), hydration status (2 levels – euhydrated/ non-euhydrated) and trial/time-of-day (3 levels – 13:50 h, 15:50 h, 17:50 h) and a random factor of participants (*n* = 73). Results revealed a significant main effect of trial on physical activity $F_{2,86}$=3.71, p=0.029 and also an interaction effect of condition by hydration status $F_{1,137}$= 4.17, p=0.043. Hence physical activity was subsequently entered into the analyses as a covariate in models of cognitive performance but was not significant with the exception of Stroop percentage correct on matching word-pairs (Table 2).

To assess the main and interaction effects of condition, hydration status, and trial/time-of-day on cognitive dependent variables, data were analysed using a mixed model analysis of variance with 3 fixed factors of condition (2 levels), hydration status (2 levels) and time-of-day (3 levels) and random factors of participants (n = 73) and physical activity as a covariate. Dependent variables consisted of PVT mean RT and lapses and Stroop RT and percentage correct for matching and non-matching word-pairs. All statistical analyses were conducted using SPSS 20.0. The denominator degree freedoms for F statistics were computed using the Satterthwaite approximation method. Uncorrected degrees of freedom are reported. LSD post-hoc contrasts were specified between levels of the fixed effect factors.

3. Results

3.1. PVT performance

Main and interaction effects on PVT mean RT and lapses are reported in Table 2. For the main effect of hydration status on mean RT non-euhydrated values were significantly higher compared to euhydrated values, when averaged over conditions and trials. For the interaction effect of hydration status by condition on PVT mean RT post-hocs showed non-euhydrated values in the *hot* condition were significantly higher compared to euhydrated values in both the *control* and *hot* conditions, when averaged over trials (Figure 1A).

For the main effect of time-of-day on lapses values were significantly higher by the 17:50 h trial compared to both the 13:50 h ($p<0.001$) and 15:50 h ($p=0.002$) trials, when averaged over hydration status and conditions. For the interaction effect of hydration status by time-of-day on lapses, post-hocs showed by the 17:50 h trial non-euhydrated values were significantly higher than euhydrated values (p<0.001), when averaged over conditions. For the interaction effect of condition by time-of-day on lapses, post-hocs showed by the 17:50 h trial values in the *hot* condition were significantly higher than the *control* condition (p=0.003), when averaged over hydration status. For the three-way interaction effect on lapses (i.e., hydration status by condition by time-of-day) post-hocs showed by the 17:50 h trial, non-euhydrated values in the *hot* condition were significantly higher than euhydrated values (p<0.001), and also significantly higher than both euhydrated (p<0.001) and non-euhydrated values (p=0.001) in the *control* condition (Figure 1B). Additionally, for lapses by the 17:50 h trial non-euhydrated values in the *hot* condition were significantly higher than both the 13:50 h (p<0.001) and 15:50 h trials (p<0.001; Figure 1B).

3.2. Stroop simple and complex cognitive measures

Main and interaction effects on Stroop RT for both matching and non-matching word-pairs are reported in Table 2. For the main effect of condition on Stroop RT for matching word-pairs values in the *control* condition were significantly higher compared to the *hot* condition, when averaged over hydration status and trials. For the interaction effect of condition by time-of-day on Stroop RT for matching word-pairs, post-hocs showed values in the *control* condition for the 13:50 h (p=0.024) and 15:50 h (p=0.019) trials were significantly higher relative to the *hot* condition. When averaged over hydration status (Figure 2A).

For the main effect of condition on Stroop RT for non-matching word-pairs values in the *hot* condition were significantly higher compared to the *control* condition, when averaged over hydration status and trials. For the main effect of time-of-day on Stroop RT for non-matching word-pairs by the 17:50 h trial values were significantly higher compared to both the 13:50 h (p=0.013) and 15:50 h (p=0.002) trials, when averaged over hydration status and conditions. For the interaction effect of hydration status by time-of-day on Stroop RT for non-matching word-pairs post-hocs showed by the 17:50 h trial non-euhydrated values were significantly higher than euhydrated values (p=0.003), when averaged over conditions (Figure 2B). Additionally, for Stroop RT on non-matching word-pairs by the 17:50 h trial non-euhydrated values in *hot* condition were significantly higher than both the 13:50 h (p=0.010) and 15:50 h trials (p=0.001; Figure 2B). There were no statistically significant main or interaction effects on Stroop percentage correct (Table 2) for both matching (Figure 2A) and non-matching word-pairs (Figure 2B).

Table 2

Results of mixed-effect ANOVAs with physical activity as a covariate, hydration status, condition and time-of-day as fixed effects and participant ID as a random effect on measures of cognitive performance.

	Physical activity			Hydration status			Condition			Time-of-day			Hydration status by condition			Hydration status by time-of-day			Condition by time-of-day			Hydration status by condition by time-of-day		
	F	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*	*F*	*df*	*p*
PVT RT	0.44	1,100	0.508	6.26	1,138	**0.014**	1.48	1,83	0.228	3.05	2,102	**0.052**	4.17	1,138	**0.043**	1.45	2,102	0.239	1.35	2,100	0.264	0.99	2,101	0.374
PVT Lapses	1.32	1,89	0.254	3.13	1,134	0.079	3.82	1,91	**0.054**	7.15	2,113	**0.001**	3.45	1,134	0.065	7.72	2,115	**0.001**	4.42	2,112	**0.014**	6.99	2,114	**0.001**
Stroop RT (M)	0.12	1,141	0.730	0.09	1,100	0.767	4.01	1,82	**0.049**	0.8	2,90	0.454	3.62	1,94	0.060	0.19	2,90	0.828	3.51	2,78	**0.035**			
Stroop % (M)	1.77	1,112	0.186	0.08	1,135	0.781	0.16	1,91	0.695	0.15	2,108	0.861	1.98	1,131	0.62	0.37	2,110	0.690	0.07	2,87	0.930			
Stroop RT (N)	0.71	1,139	0.403	3.47	1,94	0.065	6.84	1,79	**0.011**	4.95	2,86	**0.009**	0.06	1,89	0.810	5.19	2,86	**0.007**	0.90	2,76	0.412			
Stroop % (N)	6.50	1,93	**0.012**	0.65	1,141	0.423	0.33	1,89	0.570	1.35	2,114	0.264	0.00	1,141	0.949	0.53	2,118	0.588	1.19	2,91	0.309			

(M) Matching (N) Non-matching

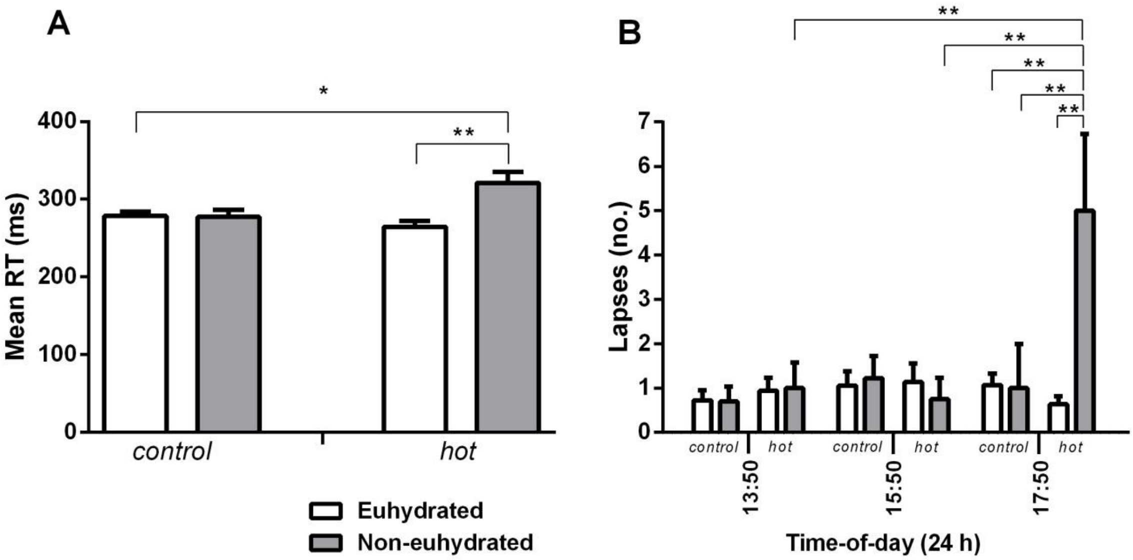

Figure 1 PVT. Panel A: PVT mean RT. Plotted as the interaction of condition by hydration status averaged over trials. Panel B: PVT lapses. Plotted as the interaction of condition by hydration status and time-of-day. Symbols denote significant LSD post-hoc differences: *p<0.05, **p<0.01. Values represent mean ± SEM.

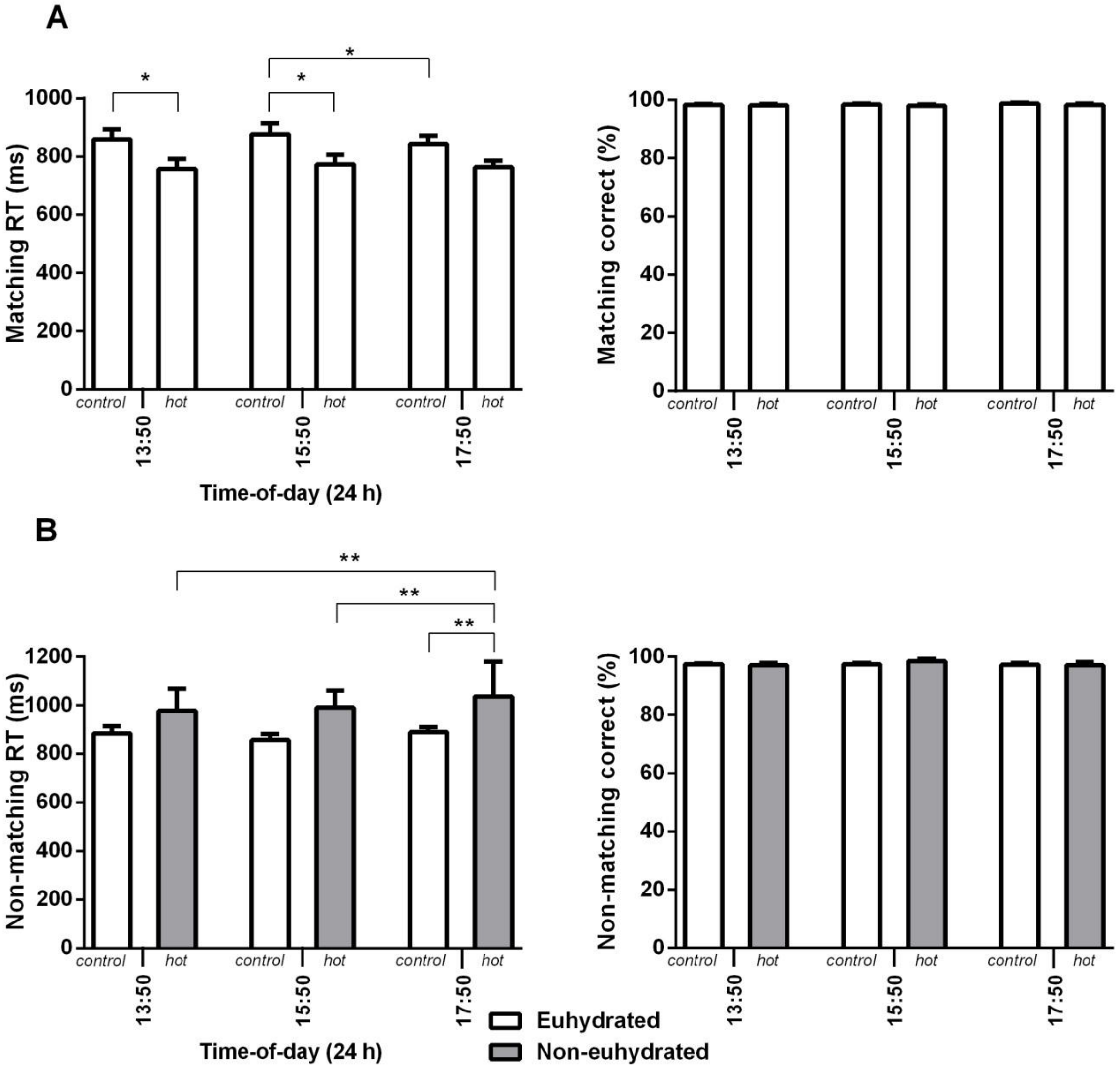

Figure 2 Stroop task. Panel A: Stroop matching word-pairs RT and percentage correct. Plotted as the interaction of condition by time-of-day, averaged over hydration status. Panel B: Stroop non-matching word-pairs RT and percentage correct. Plotted as the interaction of hydration status by time-of-day, averaged over conditions. Symbols denote significant LSD post-hoc differences: *p<0.05, **p≤0.01. Values represent mean ± SEM.

4. Discussion

The aim of the present study was to examine the effect of hydration in either temperate or warm conditions on the cognitive performance of firefighters carrying out wildfire suppression tasks. Results demonstrated PVT performance remained relatively stable in thermoneutral temperature regardless of *approaching dehydration,* although in the heat performance impairments on both PVT mean RT and lapses were observed. For the Stroop task results showed the percentage of correct responses was not significantly affected by temperature, hydration status or time-of-day (see Section 5.2.2). Results also showed for the Stroop task response times to matching word-pairs were impaired in temperate conditions compared to the heat, over the early- and mid-afternoon trials. However, on non-matching word-pairs, reaction time performance was most impaired when *approaching dehydration* by the late-afternoon, regardless of external temperature. For the results to provide contrast to other research where comparisons are made, it should be noted that non-euhydrated values correspond to a body weight loss of < 1%. While *approaching dehydration* values correspond to body weight losses in the range of 3-5% (Popowski et al., 2001).

For measures of the PVT, *approaching dehydration* was associated with different outcomes in the heat as compared to a thermoneutral temperature range. For example, PVT mean RT under normal temperatures remained stable regardless of *approaching dehydration*. However in the heat *approaching dehydration* resulted in significantly impaired performance relative to the *hot* hydrated, *control* hydrated and *approaching dehydration* groups. This is consistent with previous research showing dehydration losses of 1-2% B_m do not typically result in cognitive impairments in cold or thermoneutral (~20°C) temperatures (Adan, 2012; Leibowitz, Abernethy, Buskirk, Bar-or, & Hennessy, 1972; Neave et al., 2001; Serwah & Marino, 2006). However, in heated environmental conditions (39-45°C T_{db}) dehydration losses of $\geq 2\%$ B_w induced from moderate exercise have resulted in cognitive declines on measures of psychomotor control (Sharma et al., 1986) and motor speed on a visuo-motor tracking task (Gopinathan et al., 1988). In contrast to the relatively stable performance of the PVT under thermoneutral temperatures with *approaching dehydration*, previous studies have reported dehydration impairs psychomotor performance regardless of the method of induction (Cian et al., 2001; Cian et al., 2000; Petri, Dropulic, & Kardum, 2006; Suhr, Hall, Patterson, & Niinistö, 2004).

For Stroop RT on non-matching word-pairs, the cognitive measure relying on the executive function of response inhibition, findings showed a speed-accuracy trade-off. That is, percentage correct remained stable over the simulated workshift for both hydrated and *approaching dehydration* groups, whilst RT became significantly slower in the *approaching dehydration* group by the late-afternoon regardless of ambient temperature. This finding is consistent with previous studies on dehydration demonstrating speed-accuracy trade-offs on complex self-paced cognitive tasks, albeit in the opposite direction, with faster response times at the expense of an increase in errors (Grego et al., 2005; Tomporowski et al., 2007). These findings are also generally consistent with research showing that regardless of the method of dehydration, deficits will result for measures of complex cognitive functions when dehydration levels exceed 2% B_m loss from passive heat or exercise alone (Cian et al., 2001; Cian et al., 2000; Ganio et al., 2011). Although in contrast to the present findings, no effects of dehydration on cognitive performance have been reported on a variety of complex tests, including the Stroop task (Szinnai et al., 2005), under numerous experimental conditions (Armstrong et al., 2012; Grego et al., 2005; Serwah & Marino, 2006; Tomporowski et al., 2007).

Findings also revealed physical activity was a significant co-variate for Stroop percentage correct for non-matching word-pairs, however performance remained relatively stable and was not affected by temperature, hydration status or time-of-day. It may be the diminishing effects of these factors is counterbalanced or even masked by the increase in arousal seen from exercise resulting in the stable performance observed. For example, performance improvements in reaction time have been observed immediately following exercise durations greater than 20 minutes (Chmura, Krysztofiak, Ziemba, Nazar, & Kaciuba-Uscilko, 1998; Collardeau, Brisswalter, & Audiffren, 2001; Collardeau, Brisswalter, Vercruyssen, Audiffren, & Goubault, 2001).

The findings of this study have a number of practical implications. Firstly, firefighter’s simple mental functions may deteriorate when *approaching dehydration* and when ambient temperatures exceed 32°C, and also if it is late in the afternoon. Presenting a significant risk as firefighters perform 12-16 h shifts during the day and night suppressing wildland fires known to reach temperatures in excess of 45°C (Teague et al., 2010). The findings also suggest that if firefighters need to maintain vigilance and react quickly that dehydration and hot temperatures may increase the risk of impaired performance. For instance when firefighters have to avoid falling debris, evade rapidly degrading environments or avoid less favourable terrains. Hence, fire agencies should be aware that a temperature range of 33-35°C provides a guide as to when firefighters aged between 29 and 32 years of age, in hotter temperatures will begin to experience a deterioration of basic mental functions as dehydration ensues.

Furthermore, firefighter’s complex mental functioning may be impaired irrespective of external temperature if they are *approaching dehydration* and it is late in the day (i.e., approximately 18:00 h). This highlights a significant issue as previous research has identified that firefighters arrive on shift dehydrated (Cuddy et al., 2008; Raines et al., 2012, 2013; Ruby et al., 2003) and either sustain that level of dehydration (Ruby et al., 2003) or increase it by the end of their work shift (Cuddy et al., 2008; Hendrie et al., 1997). Approaching dehydration late in the shift may impede the ability to plan, co-ordinate and execute life-saving exit strategies based on incoming cues from the environment (e.g. recognising smoke patterns that indicate changing conditions) and central information being relayed about the changing fire conditions. Increasing fluid and food supplies at staging areas and reminding crews to load firefighting vehicles with ample food and drink supplies for the duration of their shift is an important strategy. Furthermore, increasing safety controls such as peer-monitoring, and reminders from superiors encouraging workers to pay attention to their fluid intake whilst deployed in hotter temperatures, as it becomes later in the afternoon would also be beneficial. Although this study has a number of important practical implications for fire agencies one limitation is that the effect on firefighters' cognitive performance from multiple days of dehydration in similar or more extreme ambient temperatures remains to be determined.

In conclusion, this study simulated a wildfire suppression shift, allowing natural in-field *ad libitum* hydrating provisions, in either temperate or hot conditions to evaluate the cognitive performance of firefighters. The results revealed that the greatest deteriorations in both simple and complex cognitive functions were associated with *approaching dehydration* late in the afternoon. Fire agencies should consider a number of safety controls to manage individual health and safety such as peer monitoring, increasing food and fluid supplies etc., in order to minimise the risk of dehydration. This would maximise the mental effectiveness of firefighters during fire suppression operations. Future research may want to overcome a limitation of this study by aiming to determine whether dehydration in extremely hot or cool ambient temperatures, or for more prolonged durations results in changes to cognitive performance. Further, assessing the temperature ranges at which cognitive performance may be susceptible to dehydration will better inform the implementation of workplace strategies and guidelines.

Acknowledgements

The authors would like to thank the rural firefighting agencies for their participation and recruiting volunteers for the study including the Country Fire Authority (CFA), Tasmania Fire Service, New South Wales Fire Service, Country Fire Service (CFS) and Australian Capital Territory Fire Service. We also thank the staff and students from Central Queensland University (Appleton Institute), and the School of Exercise and Nutrition Sciences at Deakin University. The project was funded by the Bushfire Cooperative Research Centre.

References

Adan, A. (2012). Cognitive performance and dehydration. *J Am Coll Nutr, 31*(2), 71-78.

Aisbett, B., Wolkow, A., Sprajcer, M., & Ferguson, S. A. (2012). "Awake, smoky, and hot": providing an evidence-base for managing the risks associated with occupational stressors encountered by wildland firefighters. *Appl Ergon, 43*(5), 916-925. doi: 10.1016/j.apergo.2011.12.013

Armstrong, L. E., Ganio, M. S., Casa, D. J., Lee, E. C., McDermott, B. P., Klau, J. F., . . . Lieberman, H. R. (2012). Mild dehydration affects mood in healthy young women. *J Nutr, 142*(2), 382-388. doi: 10.3945/jn.111.142000

Armstrong, L. E., Maughan, R. J., Senay, L. C., & Shirreffs, S. M. (2013). Limitations to the use of plasma osmolality as a hydration biomarker. *Am J Clin Nutr, 98*(2), 503-504. doi: 10.3945/ajcn.113.065466

Cheuvront, S. N., Ely, B. R., Kenefick, R. W., & Sawka, M. N. (2010). Biological variation and diagnostic accuracy of dehydration assessment markers. *Am J Clin Nutr, 92*(3), 565-573. doi: 10.3945/ajcn.2010.29490

Cheuvront, S. N., Kenefick, R. W., & Charkoudian, N. (2013). Reply to LE Armstrong et al. *Am J Clin Nutr, 98*(2), 505-506. doi: 10.3945/ajcn.113.065482

Cheuvront, S. N., Kenefick, R. W., Sollanek, K. J., Ely, B. R., & Sawka, M. N. (2013). Water-deficit equation: systematic analysis and improvement. *Am J Clin Nutr, 97*(1), 79-85. doi: 10.3945/ajcn.112.046839

Chmura, J., Krysztofiak, H., Ziemba, A. W., Nazar, K., & Kaciuba-Uscilko, H. (1998). Psychomotor performance during prolonged exercise above and below the blood lactate threshold. *Eur J Appl Physiol Occup Physiol, 77*(1-2), 77-80.

Cian, C., Barraud, P. A., Melin, B., & Raphel, C. (2001). Effects of fluid ingestion on cognitive function after heat stress or exercise-induced dehydration. *International Journal of Psychophysiology, 42*(3), 243-251. doi: http://dx.doi.org/10.1016/S0167-8760(01)00142-8

Cian, C., Koulmann, N., Barraud, P. A., Raphel, C., Jimenez, C., & Melin, B. (2000). Influences of variations in body hydration on cognitive function: Effect of hyperhydration, heat stress, and exercise-induced dehydration. *Journal of Psychophysiology, 14*(1), 29-36. doi: 10.1027//0269-8803.14.1.29

Collardeau, M., Brisswalter, J., & Audiffren, M. (2001). Effects of a prolonged run on simple reaction time of well trained runners. *Percept Mot Skills, 93*(3), 679-689. doi: 10.2466/pms.2001.93.3.679

Collardeau, M., Brisswalter, J., Vercruyssen, F., Audiffren, M., & Goubault, C. (2001). Single and choice reaction time during prolonged exercise in trained subjects: influence of carbohydrate availability. *Eur J Appl Physiol, 86*(2), 150-156.

Cuddy, J. S., Gaskill, S. E., Sharkey, B. J., Harger, S. G., & Ruby, B. C. (2007). Supplemental feedings increase self-selected work output during wildfire suppression. *Med Sci Sports Exerc, 39*(6), 1004-1012. doi: 10.1249/mss.0b013e318040b2fb

Cuddy, J. S., Ham, J. A., Harger, S. G., Slivka, D. R., & Ruby, B. C. (2008). Effects of an Electrolyte Additive on Hydration and Drinking Behavior During Wildfire Suppression. *Wilderness & Environmental Medicine, 19*(3), 172-180. doi: http://dx.doi.org/10.1580/07-WEME-OR-114.1

Dorrian, J., Dinges, D., & Rogers, N. L. (2005). *Psychomotor vigilance performance : Neurocognitive assay sensitive to sleep loss*. New York: Marcel Dekker.

Dorrian, J., Hussey, F., & Dawson, D. (2007). Train driving efficiency and safety: examining the cost of fatigue. *J Sleep Res, 16*(1), 1-11. doi: 10.1111/j.1365-2869.2007.00563.x

Dorrian, J., Roach, G. D., Fletcher, A., & Dawson, D. (2006). The effects of fatigue on train handling during speed restrictions. *Transportation Research Part F: Traffic Psychology and Behaviour, 9*(4), 243-257. doi: http://dx.doi.org/10.1016/j.trf.2006.01.003

Dorrian, J., Roach, G. D., Fletcher, A., & Dawson, D. (2007). Simulated train driving: fatigue, self-awareness and cognitive disengagement. *Appl Ergon, 38*(2), 155-166. doi: 10.1016/j.apergo.2006.03.006

Ferguson, S. A., Aisbett, B., Jay, S. M., Onus, K., Lord, C., Sprajcer, M., & Thomas, M. J. (2011). Design of a valid simulation for researching physical, physiological and cognitive performance in volunteer firefighters during bushfire deployment *Proceedings of Bushfire CRC & AFAC 2011 Conference Science Day* (pp. 196-204): Bushfire Cooperative Research Centre.

Ganio, M. S., Armstrong, L. E., Casa, D. J., McDermott, B. P., Lee, E. C., Yamamoto, L. M., . . . Lieberman, H. R. (2011). Mild dehydration impairs cognitive performance and mood of men. *Br J Nutr, 106*(10), 1535-1543. doi: 10.1017/s0007114511002005

Gaskill, S., & Ruby, B. (2004). Hours of Reported Sleep during Random Duty Assignments for Four Type I Wildland Firefighter Crews.

Gopinathan, P. M., Pichan, G., & Sharma, V. M. (1988). Role of dehydration in heat stress-induced variations in mental performance. *Arch Environ Health, 43*(1), 15-17. doi: 10.1080/00039896.1988.9934367

Grego, F., Vallier, J. M., Collardeau, M., Rousseu, C., Cremieux, J., & Brisswalter, J. (2005). Influence of exercise duration and hydration status on cognitive function during prolonged cycling exercise. *Int J Sports Med, 26*(1), 27-33. doi: 10.1055/s-2004-817915

Hendrie, A., Brotherhood, J., Budd, G., Jeffery, S., Beasley, F., Costin, B., . . . Dawson, M. (1997). Project Aquarius 8. Sweating, Drinking, and Dehydration in Men Suppressing Wildland Fires. *International Journal of Wildland Fire, 7*(2), 145-158. doi: http://dx.doi.org/10.1071/WF9970145

Leibowitz, H. W., Abernethy, C. N., Buskirk, E. R., Bar-or, O., & Hennessy, R. T. (1972). The effect of heat stress on reaction time to centrally and peripherally presented stimuli. *Hum Factors, 14*(2), 155-160.

Neave, N., Scholey, A. B., Emmett, J. R., Moss, M., Kennedy, D. O., & Wesnes, K. A. (2001). Water ingestion improves subjective alertness, but has no effect on cognitive performance in dehydrated healthy young volunteers. *Appetite, 37*(3), 255-256. doi: 10.1006/appe.2001.0429

Petri, N. M., Dropulic, N., & Kardum, G. (2006). Effects of voluntary fluid intake deprivation on mental and psychomotor performance. *Croat Med J, 47*(6), 855-861.

Phillips, Payne, W., Lord, C., Netto, K., Nichols, D., & Aisbett, B. (2012). Identification of physically demanding tasks performed during bushfire suppression by Australian rural firefighters. *Appl Ergon, 43*(2), 435-441. doi: 10.1016/j.apergo.2011.06.018

Popowski, L. A., Oppliger, R. A., Patrick Lambert, G., Johnson, R. F., Kim Johnson, A., & Gisolf, C. V. (2001). Blood and urinary measures of hydration status during progressive acute dehydration. *Med Sci Sports Exerc, 33*(5), 747-753.

Raines, J., Snow, R., Nichols, D., & Aisbett, B. (2015). Fluid intake, hydration, work physiology of wildfire fighters working in the heat over consecutive days. *Ann Occup Hyg, 59*(5), 554-565. doi: 10.1093/annhyg/meu113

Raines, J., Snow, R., Petersen, A., Harvey, J., Nichols, D., & Aisbett, B. (2012). Pre-shift fluid intake: Effect on physiology, work and drinking during emergency wildfire fighting. *Applied Ergonomics, 43*(3), 532-540. doi: http://dx.doi.org/10.1016/j.apergo.2011.08.007

Raines, J., Snow, R., Petersen, A., Harvey, J., Nichols, D., & Aisbett, B. (2013). The effect of prescribed fluid consumption on physiology and work behavior of wildfire fighters. *Applied Ergonomics, 44*(3), 404-413. doi: http://dx.doi.org/10.1016/j.apergo.2012.10.002

Ruby, B. C., Schoeller, D. A., Sharkey, B. J., Burks, C., & Tysk, S. (2003). Water turnover and changes in body composition during arduous wildfire suppression. *Medicine and science in sports and exercise, 35*(10), 1760-1765. doi: 10.1249/01.mss.0000089348.39312.4d

Serwah, N., & Marino, F. E. (2006). The combined effects of hydration and exercise heat stress on choice reaction time. *Journal of Science and Medicine in Sport, 9*(1–2), 157-164. doi: http://dx.doi.org/10.1016/j.jsams.2006.03.006

Sharma, V. M., Sridharan, K., Pichan, G., & Panwar, M. R. (1986). Influence of heat-stress induced dehydration on mental functions. *Ergonomics, 29*(6), 791-799. doi: 10.1080/00140138608968315

Suhr, J. A., Hall, J., Patterson, S. M., & Niinistö, R. T. (2004). The relation of hydration status to cognitive performance in healthy older adults. *International Journal of Psychophysiology, 53*(2), 121-125. doi: http://dx.doi.org/10.1016/j.ijpsycho.2004.03.003

Szinnai, G., Schachinger, H., Arnaud, M. J., Linder, L., & Keller, U. (2005). Effect of water deprivation on cognitive-motor performance in healthy men and women. *Am J Physiol Regul Integr Comp Physiol, 289*(1), R275-280. doi: 10.1152/ajpregu.00501.2004

Tabachnick, B. G., & Fidell, L. S. (2007). *Using multivariate statistics* (5th ed.). Boston: Pearson/Allyn &amp; Bacon.

Teague, B., McLeod, R., & Pascoe, S. (2010). Final report, 2009 victorian bushfires royal commission. *Parliament of Victoria, Melbourne Victoria, Australia*.

Thorne, D., Johnson, D., Redmond, D., Sing, H., Belenky, G., & Shapiro, J. (2005). The Walter Reed palm-held psychomotor vigilance test. *Behavior Research Methods, 37*(1), 111-118. doi: 10.3758/BF03206404

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychol (Amst), 112*(3), 297-324.

Tomporowski, P. D., Beasman, K., Ganio, M. S., & Cureton, K. (2007). Effects of dehydration and fluid ingestion on cognition. *Int J Sports Med, 28*(10), 891-896. doi: 10.1055/s-2007-965004